TIME DILATION AND QUASAR VARIABILITY

M. R. S. Hawkins
University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, Scotland, UK
mrsh@roe.ac.uk

ABSTRACT

The timescale of quasar variability is widely expected to show the effects of time dilation. In this paper we analyse the Fourier power spectra of a large sample of quasar light curves to look for such an effect. We find that the timescale of quasar variation does not increase with redshift as required by time dilation. Possible explanations of this result all conflict with widely held consensus in the scientific community.

Subject headings: cosmology: miscellaneous

1. INTRODUCTION

Time dilation is a fundamental property of an expanding universe. In fact the increase of timescale by a factor of $(1+z)$ represents a basic link between redshift and time which is essentially related to the definition of time and is independant of cosmological model parameters. As a consequence, time dilation has generally been assumed to be a property of the Universe even though it has proved hard to measure directly. Recently there has been new interest in time dilation as a result of experiments where its effect is large and must be taken into account.

There have been a number of claims by groups working on gamma ray bursters (Deng & Schaefer 1998) that time dilation is seen in the stretching of peak-to-peak timescales. This has then been used to support the argument that the bursts are at cosmological distances. It is not clear however that the argument can be inverted to provide convincing evidence for the existence of time dilation.

A more direct observation of time dilation has come from the measurement of the decay time of distant supernova light curves and spectra (Leibundguat et al. 1996; Goldhaber et al. 1997; Riess et al. 1997). Here one can make a good case that the rest frame timescale is known, and hence directly detect any time dilation effect at high redshift. The results so far published are very convincing, and strongly imply that time dilation has been observed.

Another situation where one would expect to see a time dilation effect is in the light curves of quasars, which are at cosmological distances and vary on a timescale of years. A number of groups have looked for time dilation in quasar light curves (Hook et al. 1994; Cristiani et al. 1996; Hawkins 1996), but so far it seems fair to say that no convincing detection has been made, although one might argue that the sample sizes and data analysis procedures were not adequate to detect the effect of time dilation if it were present.

2. POWER SPECTRUM ANALYSIS

In order to measure time dilation in quasar light curves it is necessary to find a way of characterising the timescale of variation. The most popular parameterisation to date has been the structure function, and several groups have measured it for samples of light curves (Hook et al. 1994; Cristiani et al. 1996), as well as predicting its shape for various models of quasar variability (Kawaguchi et al. 1998). The autocorrelation function, which is closely related to the structure function, has also been used (Hawkins 1996). The main drawback of these functions is that the points are not independent of each other, which causes difficulties with error analysis, and makes them very hard to interpret.

Fourier power spectrum analysis has not been used much in the analysis of quasar light curves, probably because it requires a long run of evenly spaced data to be effective. However, given such a dataset it provides some significant advantages over other methods, perhaps the most important of which is the relative ease with which it may be interpreted. In this paper we apply it to a large sample of quasars which have been homogeneously monitored every year for 24 years (Hawkins 1996).

The survey is based on a long series of UK 1.2m Schmidt plates of the ESO/SERC field 287 centred on 21h 38m, -45°. The plates were taken over a variety of timescales from hours to years, and in various passbands including B, R and U. Of particular relevance to this paper is a regular yearly monitoring of the field in the B_J passband (Kodak IIIa-J emulsion with a Schott GG395 filter) from 1977 till 2000. For most years four plates were obtained, but in a few cases it was only possible to obtain one. A similar series of 18 yearly measures was also obtained in R, from 1983 till 2000. The plates were measured by the COSMOS or SuperCOSMOS machines at the University of Edinburgh to give a catalogue of photometric measures for some 200,000 objects in the central 19 square degrees of the field. The photometric error on an observation from a single plate is about 0.08 mag. When 4 plates were available the mean magnitude was used giving a photometric error of about 0.04 mag. More details of the reduction procedure and error analysis are given by Hawkins (1996) and references therein.

The quasars in the field were found by a variety of techniques, including ultra-violet excess, variability, blue drop-out and objective prism. Altogether some 600 quasars have now been identified, with confirming redshifts in the range $0.1 < z < 3.5$. There are sufficient numbers that the quasars can be binned in both redshift and luminosity to avoid the well-known degeneracy between these two parameters. All the quasars used in this study fluctuated significantly in brightness over the 24 year monitoring period, with an amplitude of mode 0.6 mag and a tail extending to 2 mag. In order to compare the spectrum of variations of subsamples of quasars from the survey, a Fourier power spectrum was calculated for each light curve. The quasars were then binned in redshift and luminosity, in such a way that each bin contained approximately 100 objects, with a total of 407 quasars used for the analysis.

For the study of time dilation we first make the assumption that the light variations are intrinsic to the quasars, and so the light curves are subject to the effects of time dilation. Thus for each light curve we rescale the time interval by a factor of $(1 + z)^{-1}$ where z is the redshift of the quasar, and re-sample the power spectra on a uniform scale. This should remove the effects of time dilation, with the result that there should be no trend of timescale with redshift. This has the effect of shifting the contributions of all quasars to higher frequencies. It is a big effect, especially for high redshift quasars, in several cases resulting in low frequency bins being completely emptied.

Fig. 1 shows the power spectra of samples of quasar light curves, binned according to redshift and luminosity. Each point represents the average of value of all the contributions to that frequency interval. The top two panels show results for two luminosity bins, with power spectra for low and high redshift quasars being represented by filled and open circles respectively. If the timescales of the quasar light curves were subject to time dilation one would expect no displacement between the two curves. In fact, a χ^2 test shows that for both luminosity bins the power spectra are not coincident at the 99% level. The two power spectra are separated by about 0.15 in the log in both luminosity bins. This is close to the offset produced by allowing for a $(1 + z)$ scale change, on the basis of the mean redshifts of the bins. There is also some indication that the power spectra have moved horizontally rather than vertically from the morphology of the distributions. The bottom two panels show similar data for two redshift bins. In this case low and high luminosity quasars are represented by closed and open circles respectively. The mean redshift for the high and low luminosity data in each plot only differs by about 0.03 in the log, and so the removal of the $(1+z)$ factor should make little difference. In fact the two luminosity bins are well separated, implying more power or shorter timescales for low luminosity objects.

We now make no assumptions about the nature of the quasar variability, but carry out the power spectrum analysis in the observer's reference frame. Fig. 2 shows power spectra of quasar light curves as for Fig. 1 but this time with no cor-

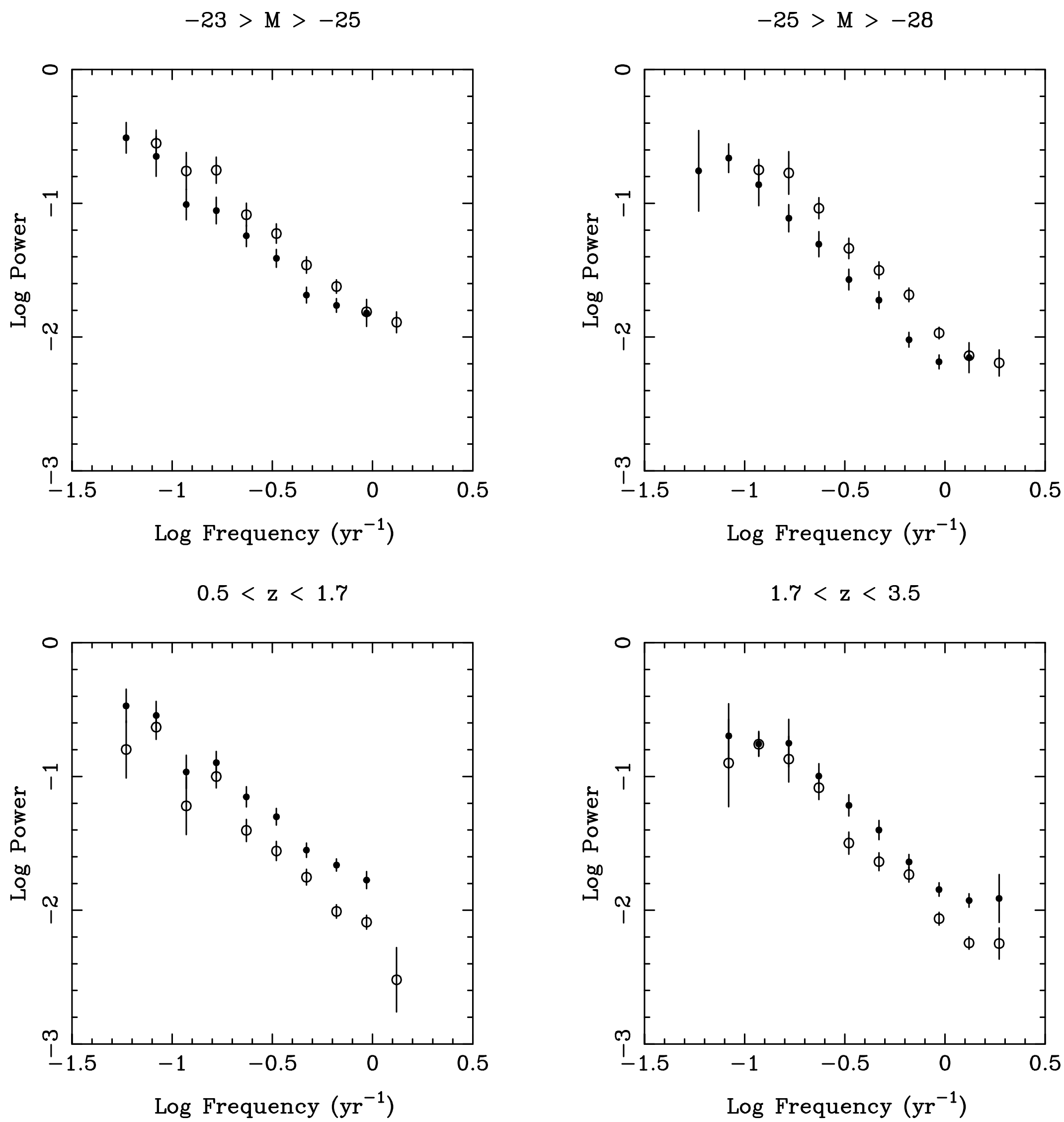

Fig. 1.— Fourier power spectra for sub-samples of quasar light curves in the quasar rest frame, with time dilation effects removed. The top two panels show data for low and high luminosity quasars. The filled and open circles are power spectra for low and high redshift objects respectively. The bottom two panels show data for low and high redshift quasars. The filled and open circles are power spectra for low and high luminosity objects respectively.

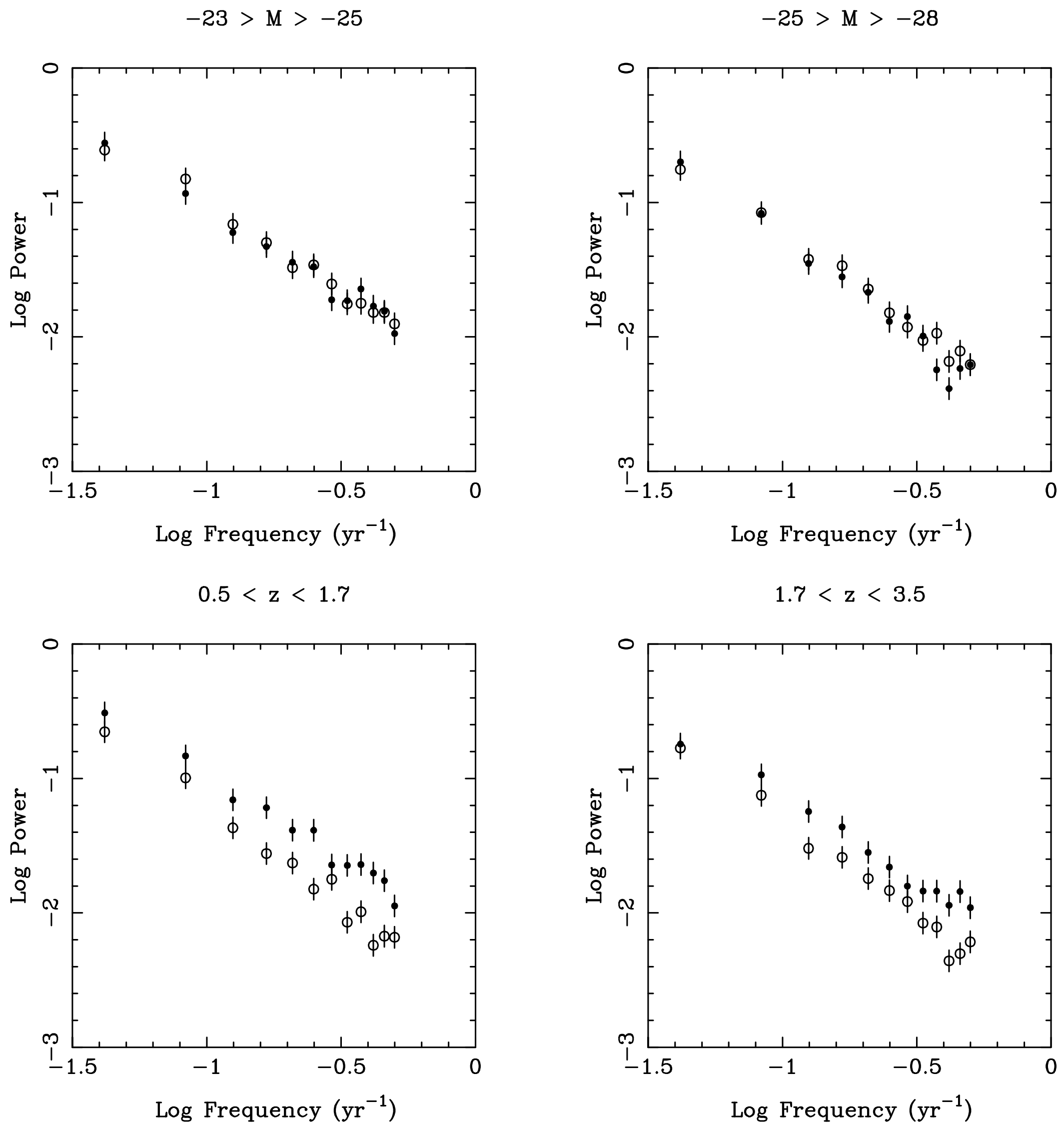

Fig. 2.— Fourier power spectra for sub-samples of quasar light curves in the observer's frame, with no allowance for time dilation. The bins are as for Fig. 1. This figure shows that the observed timescale of quasar variation does not change with redshift for both luminosity bins. It also shows that low luminosity quasars have more short timescale power than more luminous ones.

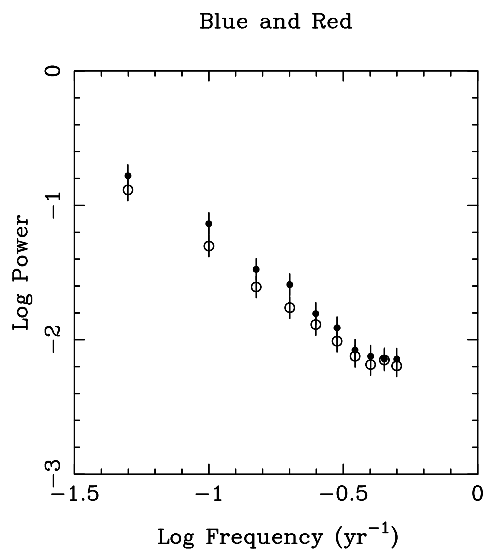

Fig. 3.— Fourier power spectra for a sample of quasars in blue (closed circles) and red (open circles) passbands, in the observer's frame.

rection for time dilation. For the two luminosity bins in the top two panels it will be seen that all spectra show well-defined linear (power law) relations. On the basis of the mean redshift for each of the bins, the effects of time dilation should result in a horizontal offset of 0.15 between the power spectra in each of the two top panels. In fact, in each case the high and low redshift data are superimposed, showing no change of timescale with redshift. This is confirmed by a χ^2 test which shows both pairs of power spectra compatible at the 30% level. The two redshift bins in the bottom panels again show well defined power laws for the power spectra, and in this case it is clear that low luminosity quasars have more power on shorter timescales. This effect can also be seen by comparing the slopes of the power spectra for low and high luminosity quasars in the top two panels, and confirms that the power spectra are consistently measuring changes in timescale.

3. DISCUSSION

The implication from Figs. 1 and 2 that quasars do not suffer the effects of time dilation is hard to avoid. There are however two possible ways out. If the timescale of quasar variation were a function of wavelength in the sense that timescales were shorter in bluer passbands then this might possibly exactly offset the effect of time dilation. However, this can be directly tested (Hawkins & Taylor 1997). Fig. 3 shows power spectra for a sample of about 200 quasar light curves in blue and red passbands. If there were a correlation of timescale with wavelength of the kind described above, then the two power spectra in Fig. 3 should be separated by 0.18 on the log scale, corresponding to the effective wavelengths of 436 nm and 665 nm for the blue and red passbands. In fact, the data for the blue light curves appear to be systematically offset from the red by 0.06 in the log, but a χ^2 test shows no significant difference at the 10% level. The only other alternative is that the timescale of quasar variation decreases by a factor $(1 + z)$ towards high redshift by some as yet unspecified physical process, to exactly cancel out the time dilation effect. Such a 'cosmic conspiracy' has no independent motivation, and would require a considerable degree of fine tuning. In fact the shape of the plots in Fig. 1 would appear to make such fine tuning an unrealistic possibility.

There would appear to be three possible ex-

planations for the lack of a time dilation effect in quasar light curves, all of which conflict with broad consensus in the astronomical community. Firstly, time dilation might not in fact be a property of the Universe, which would effectively mean that the Universe was not expanding. Apart from the overwhelming support for the big bang theory, the direct measurements of time dilation quoted above strongly argue against this. The second possibilty is that quasars are not at cosmological distances. This is an argument which was hotly disputed in the 1970s, with an emerging consensus favouring cosmological distances. This has subsequently been strongly confirmed by studies of quasar host galaxies at high redshift. The third possibility is that the observed variations are not intrinsic to the quasars but caused by some intervening process at lower redshift, such as gravitational microlensing. Although this idea has been strongly argued (Hawkins 1996), there is an opposing view that variations in quasars are dominated by instabilities in the central accretion disc. The reality of this mode of variability in active galactic nuclei is supported by detailed observations of Seyfert galaxies (Peterson et al. 1999) and gravitationally lensed quasars (Kundić et al. 1997), where the presence of intrinsic variations cannot be in doubt. The debate centres on whether this mechanism is responsible for the long timescale large amplitude variations which dominate the power spectra discussed in this paper.

4. CONCLUSIONS

Taking the various arguments outlined above at face value, and accepting the case against microlensing, there does not appear to be a satisfactory explanation for the absence of a time dilation effect in quasar power spectra. The arguments resting on an expanding Universe and cosmological distances for quasars seem beyond challenge. The argument against microlensing is not so secure. Apart from the statistical evidence from quasar light curves (Hawkins 1996), microlensing has been unambiguously shown to take place in gravitationally lensed quasar systems (Pelt et al. 1998), and dominates at long timescales. If this were a general phenomenon in quasars at cosmological distances then the apparent absence of a time dilation effect in quasar light curves would be explained.

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